Picosecond response times in GaAs/AlGaAs core/shell nanowire-based photodetectors

Eric M. Gallo,[1] Guannan Chen,[1] Marc Currie,[2] Terrence McGuckin,[1] Paola Prete,[3] Nico Lovergine,[4] Bahram Nabet,[5] and Jonathan E. Spanier[1,a)]
[1]*Department of Materials Science & Engineering, Drexel University, Philadelphia, Pennsylvania 19104, USA*
[2]*Optical Sciences Division, U.S. Naval Research Laboratory, Washington, DC 20375, USA*
[3]*Istituto per la Microelettronica e Microsistemi (IMM), Consiglio Nazionale delle Ricerche (CNR), Lecce I-73100, Italy*
[4]*Department of Innovation Engineering, University of Salento, Lecce I-73100, Italy*
[5]*Department of Electrical and Computer Engineering, Drexel University, Philadelphia, Pennsylvania 19104, USA*

(Received 21 April 2011; accepted 24 May 2011; published online 17 June 2011)

High-speed metal-semiconductor-metal (MSM) photodetectors based on Schottky-contacted core/shell GaAs/AlGaAs and bare GaAs nanowires were fabricated and characterized. The measured core/shell temporal response has a ~10 ps full-width at half-maximum and an estimated corrected value less than 5 ps. The bare GaAs devices exhibit a slower response (~35 ps) along with a slow decaying persistent photocurrent (~80 s). The core/shell devices exhibit significantly improved dc and high-speed performance over bare nanowires and comparable performance to planar MSM photodetectors. The picosecond temporal response, coupled with picoampere dark current, demonstrate the potential for core/shell nanowires in high-speed imaging arrays and on-chip optical interconnects. © *2011 American Institute of Physics*. [doi:10.1063/1.3600061]

GaAs-based metal-semiconductor-metal (MSM) devices offer a simple and effective device geometry for the creation of high-speed photodetectors. The addition of an AlGaAs barrier, when properly designed, has been shown to further improve performance.[1,2] The higher band gap layer reduces dark current and decreases surface recombination while increasing sensitivity and quantum efficiency. AlGaAs capping layers between 30 and 60 nm have been shown to improve the time response of devices as well.[1] III-V based nanowire devices have already shown strong potential for creating high performance optical detectors[3–6] while growth on Si substrates indicates their potential to as an integrated component within CMOS electronics.[7] Additionally a wavelength and polarization dependence has been seen in the optical responses of nanowire devices, further increasing their versatility for use as receivers.[3] High-speed testing results have been reported for several nanowire-based detectors, including ZnO (μs),[8] intersecting InP (ps)[9] and carbon nanotubes (ps)[10] but no results have yet been reported on GaAs-based nanowire detectors.

In this letter, we present experimental results and analysis of the dc and high-speed properties of core/shell GaAs/AlGaAs nanowire and bare GaAs nanowire detectors. The devices are fabricated as MSM devices with Schottky contacts. The core/shell devices demonstrate full-width half-maximum (FWHM) values of 10 ps and shorter, comparable to similar planar devices[2,11] and significantly faster than the bare core devices (~35 ps). The results are instrument-limited and conservative estimates suggest speeds twice as fast as those measured may be possible.

GaAs nanowire cores used for this letter were grown by Au-catalyst assisted metal-organic vapor phase epitaxy on GaAs substrates with diameters between 50 and 60 nm. For core/shell wires, core growth was followed a 50–60 nm AlGaAs shell and a 5–10 nm GaAs capping layer grown using conventional epitaxy with no intentional doping. The thin GaAs capping layer is incorporated to prevent oxidation of the underlying AlGaAs shell and subsequent defect formation within the core.[12] The aluminum content in the shell is estimated to be 33%.[13] Additional growth details and optical characterization of the wires can be found in Ref. 13. Gating on devices fabricated with both core/shell and bare nanowires show slightly p-type behavior, attributed to unintentional doping due to precursor contaminants during growth.[14]

For detector fabrication the core/shell nanowires were dispersed from an isopropyl alcohol suspension onto prepatterned substrates. Sapphire substrates were used to reduce parasitic capacitance. Electrodes were patterned using electron beam lithography, followed by native oxide removal in a dilute HCl solution and subsequent deposition of Pd/Ti/Au electrodes. After lift-off the devices were subjected to rapid thermal annealing in N_2 for 20 s at 425 °C.[15] All contacts were patterned with 2 μm spacing and 1 μm width. The electrode geometry was not optimized for high-speed measurements and no waveguides were implemented. Bare GaAs nanowire detectors were fabricated in a similar fashion with Ti/Au contacts.

Measurements of the dc optical properties were performed in atmosphere using a tunable cw Ti-sapphire laser pumped by a multiline Ar-ion laser and focused through an objective. Current-voltage characteristics were collected over a range of incident powers at 800 nm. The spot size of the incident radiation was estimated to be 200 ± 50 μm in diameter. High-speed responses were collected in atmosphere using a tunable Ti-sapphire laser with 80 fs pulse width. 60 GHz probes were used to electrically bias the sample and data was taken through a bias-T using a 50 GHz

a)Electronic mail: spanier@drexel.edu.

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE	**JUN 2011**
2. REPORT TYPE	
3. DATES COVERED	**00-00-2011 to 00-00-2011**
4. TITLE AND SUBTITLE	**Picosecond response times in GaAs/AlGaAs core/shell nanowire-based photodetectors**
5a. CONTRACT NUMBER	
5b. GRANT NUMBER	
5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)	
5d. PROJECT NUMBER	
5e. TASK NUMBER	
5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	**Drexel University,Department of Materials Science and Engineering,Philadelphia,PA,19104**
8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	
10. SPONSOR/MONITOR'S ACRONYM(S)	
11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT	**Approved for public release; distribution unlimited**
13. SUPPLEMENTARY NOTES	
14. ABSTRACT	
15. SUBJECT TERMS	

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Same as Report (SAR)**	**3**	

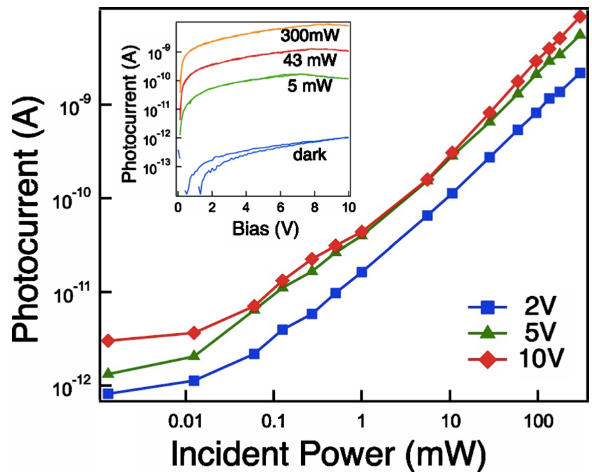

FIG. 1. (Color online) Photocurrent of representative core/shell device collected as a function of laser power (800 nm) at three different bias voltages; inset: representative dark current traces of core/shell and bare nanowire devices.

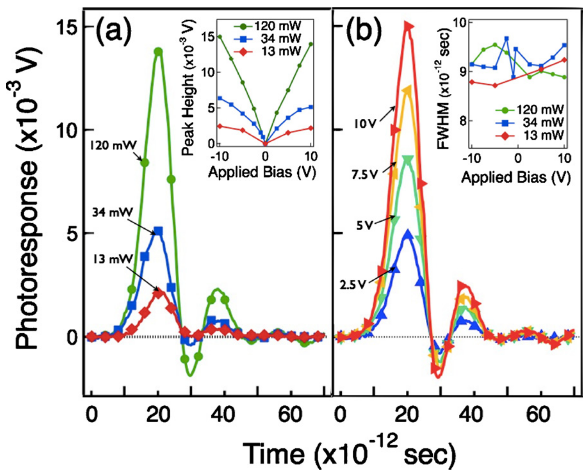

FIG. 2. (Color online) Time responses for core/shell detectors at selected (a) incident powers and (b) biases. Insets: measured peak heights and FWHM values.

sampling oscilloscope. Power measurements shown are time-averaged taken inline.

Both core/shell and bare GaAs nanowire detectors showed dark current values in the low picoampere range at 5 V bias with several devices demonstrating dark currents below the measurable range of our characterization setup. Along with this small dark current, two-terminal capacitances under 20 fF were measured for several illumination and bias values. This low capacitance is crucial in achieving high-speed operation. Plotting the photoresponse as a function of incident power for a representative core/shell device (Fig. 1) shows an estimated responsivity of 0.1 mA/W,[16] linear over approximately three orders of magnitude of incident power. The nanowire devices show a strong linear polarization dependence and all optical measurements were taken with polarization set to maximize signal strength. Bare GaAs nanowire detectors showed much lower responsivities, near 0.02 mA/W. Typical current-voltage traces of a core/shell device in dark and under selected optical powers is provided in Fig. 1, inset, showing responses similar to planar MSM detectors.[2,11]

The response times of several core/shell nanowire detectors were measured under the high-speed pulsed Ti-sapphire laser. The incident beam was defocused, polarization optimized, and positioned to maximize signal strength. Due to the low currents produced by these devices, the system was limited to higher incident powers to achieve a signal large enough to record on the oscilloscope.

Figure 2 provides two sets of representative traces with selected applied voltages and incident powers. Changing the incident power and applied bias strongly affected the amplitude of the peak response [Fig. 2(a), inset] but created little change in FWHM (~9 ps), fall time (~5 ps), and rise time (~8 ps) as would be expected in a planar MSM device[2] [Fig. 2(b), inset]. The 9 ps FWHM approaches the limits of the measurement setup, indicating some of the time response may be dominated by the probes and oscilloscope. Several of the devices exhibited asymmetric behavior in their dc photoresponse, which could be seen in a variation in the peak height of traces with opposite polarity, indicating that the peak height was being determined by the device and not a parasitic conduction path. The damped oscillations observed after the initial peak are primarily an artifact of the measurement system arising from coupling and transmission of the electrical pulse to the oscilloscope. The results indicate the lower limits of performance of these devices.

The core/shell detector responses were compared with bare GaAs nanowire detectors (Fig. 3). The bare nanowire had a significantly reduced and noisier response than that of the core/shell devices and a signal was only detectable at the largest incident power and applied bias. The bare GaAs nanowire detectors showed a fast initial response, followed by a slow tail, with a measured FWHM of 35 ps, rise time of 6 ps, and fall time of 130 ps. These wires also showed an additional very slow response, on the order of 80 s decay time, under near dc conditions. Figure 3, inset (a) plots the response over several minutes after illumination (tungsten lamp source) has been removed, demonstrating a persistent photocurrent. Similar results have been reported for ZnO nanowires.[8] The core/shell devices showed no measurable persistent response under similar circumstances. A normalized frequency response for both device types is shown in Fig. 3, inset (b), with the core/shell devices showing −3 dB value near 25 GHz. A recent report on the optical properties of similar wires found that the dc photoresponse of bare cores were dominated by charged surface trap states, the discharge of which may be the source of the slow decaying persistent photocurrent.[17] Quantum efficiency estimates for these devices vary greatly due to the approximate value of the laser spot size; however, using the high speed measurement results, a value of 13.5% at 800 nm was calculated.[18]

The overall time response is estimated by the convolution of the response times of each element, assuming each element's time response is independent of the others. Under the assumption that the laser, oscilloscope and device have Gaussian time responses then the time-domain convolution of these will produce a Gaussian response whose variance is the sum of the individual variances. The measured time response is therefore the square root of the variance, or the square root of the sum of the squares of the individual responses from the laser, oscilloscope and device, as described in (Ref. 19)

$$\tau_{\text{measured}} = \sqrt{\tau_{\text{actual}}^2 + \tau_{\text{osc}}^2 + \tau_{\text{laser}}^2}, \tag{1}$$

where τ_{actual} is the device time constant, while τ_{osc} and τ_{laser} are those of the sampling oscilloscope and the laser pulse

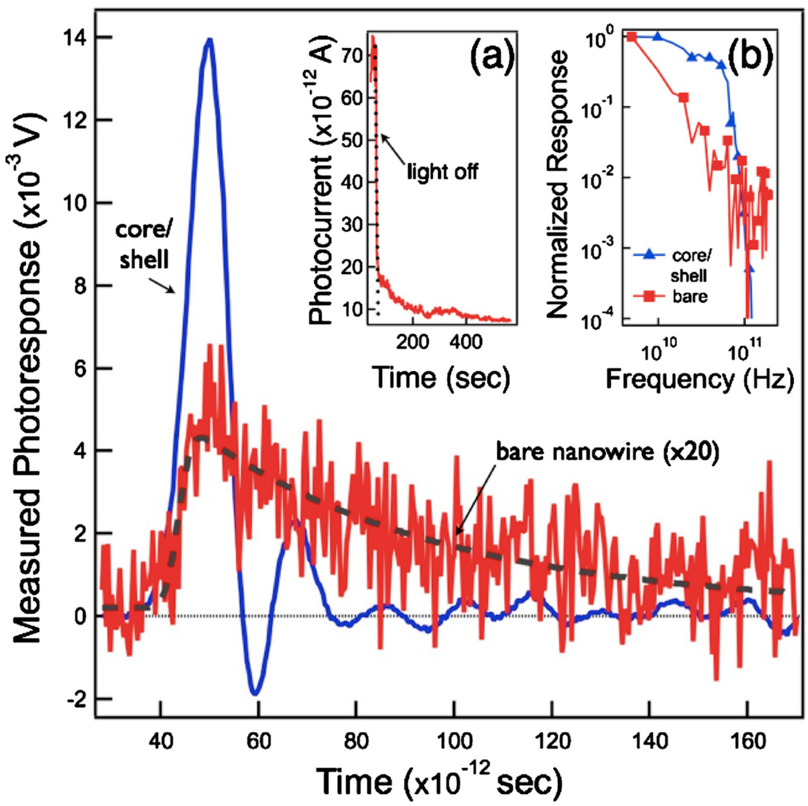

FIG. 3. (Color online) Representative time response of a core/shell nanowire and bare GaAs nanowire detectors under 120 W incident illumination and 10 V applied bias. A best fit line is provided for the bare GaAs response for clarity. Inset (a): slow time scale response of a bare GaAs nanowire detector; arrow indicates when illumination was removed and inset (b): normalized frequency response of the both detectors.

width, respectively. Assuming 7 ps rise time from the oscilloscope and 80 fs laser pulse width, a corrected value for the FWHM of the core/shell detectors is found to be near 5 ps. Electro-optic sampling methods would be necessary to more precisely characterize the true response time of these devices.[10] The response is close to but faster than the expected transit time-limited response from a 2 μm device of ~20 ps, suggesting collection may be dominated by the area near the contacts.

We have demonstrated the high-speed time response of core/shell GaAs/AlGaAs nanowire devices. The devices show a measured FWHM of less than 10 ps with an estimated 5 ps FWHM after correcting for instrument limitations. This response is considerably faster than bare GaAs detectors and comparable with planar MSM structures of similar material and structure. The lower responsivity may be improved by including absorption enhancement techniques, such as a distributed Bragg reflector and antireflective coating. Significantly the devices exhibited very low dark currents and capacitance values, making them strong candidates for elements in high-speed imaging arrays and potentially for on-chip optical interconnects.

This work at Drexel was supported by the NSF (Grant No. DMR-0907381) and in part by the U.S. Army Research Office (Grant No. W911NF-08-1-0067). E.M.G. was supported in part by the NSF GK-12 Graduate Fellowship (Grant No. DGE-0538476) and M.C. was supported by the Office of Naval Research. The authors would also like to thank Michelle Sipics for assistance in manuscript preparation.

[1]R.-H. Yuang, J.-L. Shieh, R.-M. Lin, H.-C. Shieh, and J.-I. Chyi, Electron Devices and Materials Symposium, 12-15 July 1994Hsinchu, Taiwan.
[2]B. Nabet, A. Cola, X. Chen, and F. Quaranta, IEEE Trans. Microwave Theory Tech. **51**, 2063 (2003).
[3]J. Wang, M. S. Gudiksen, X. Duan, Y. Cui, and C. M. Lieber, Science **293**, 1455 (2001).
[4]X. Jiang, Q. Xiong, S. Nam, F. Qian, Y. Li, and C. M. Lieber, Nano Lett. **7**, 3214 (2007).
[5]S. Thunich, L. Prechtel, D. Spirkoska, G. Abstreiter, A. Fontcuberta i Morral, and A. Holleitner, Appl. Phys. Lett. **95**, 083111 (2009).
[6]C. Soci, A. Zhang, X.-Y. Bao, H. Kim, Y. Lo, and D. Wang, J. Nanosci. Nanotechnol. **10**, 1430 (2010).
[7]T. Mårtensson, C. P. T. Svensson, B. A. Wacaser, M. W. Larsson, W. Seifert, K. Deppert, A. Gustafsson, L. R. Wallenberg, and L. Samuelson, Nano Lett. **4**, 1987 (2004).
[8]C. Soci, A. Zhang, B. Xiang, S. A. Dayeh, D. P. R. Aplin, J. Park, X. Y. Bao, Y. H. Lo, and D. Wang, Nano Lett. **7**, 1003 (2007).
[9]V. J. Logeeswaran, A. Sarkar, M. S. Islam, N. P. Kobayashi, J. Straznicky, X. Li, W. Wu, S. Mathai, M. R. T. Tan, S.-Y. Wang, and R. S. Williams Appl. Phys. A: Mater. Sci. Process. **91**, 1 (2008).
[10]L. Prechtel, L. Song, S. Manus, D. Schuh, W. Wegscheider, and A. W. Holleitner, Nano Lett. **11**, 269 (2011).
[11]J.-I. Chyi, Y.-J. Chien, R.-H. Yuang, J.-L. Shieh, J.-W. Pan, and J.-S. Chen, IEEE Photon. Technol. Lett. **8**, 1525 (1996).
[12]S. Perera, M. A. Fickenscher, H. E. Jackson, L. M. Smith, J. M. Yarrison-Rice, H. J. Joyce, Q. Gao, H. H. Tan, C. Jagadish, and X. Zhang, Appl. Phys. Lett. **93**, 053110 (2008).
[13]P. Prete, F. Marzo, P. Paiano, N. Lovergine, G. Salviati, L. Lazzarini, and T. Sekiguchi, J. Cryst. Growth **310**, 5114 (2008).
[14]G. Chen, E. M. Gallo, J. Burger, B. Nabet, A. Cola, P. Prete, N. Lovergine, and J. E. Spanier, Appl. Phys. Lett. **96**, 223107 (2010).
[15]H.-Y. Nie and Y. Nannichi, Jpn. J. Appl. Phys., Part 1 **30**, 906 (1991).
[16]The calculation of responsivity includes the full diameter of the core/shell nanowire (175 nm).
[17]O. Demichel, M. Heiss, J. Bleuse, H. Mariette, and A. Fontcuberta i Morral, Appl. Phys. Lett. **97**, 201907 (2010).
[18]The calculation of external quantum efficiency assumed a 200 μm laser spot diameter and included the shell and capping layer. Quantum efficiency was determined by evaluating the incident photons in a single pulse and comparing that value to the integrated high-speed response, assuming the measured signal dropped across a bias-T with a characteristic impedance of 50 Ω.
[19]G. P. Agrawal, *Fiber-Optic Communication Systems* (Wiley, New York, 2002), p. 194.